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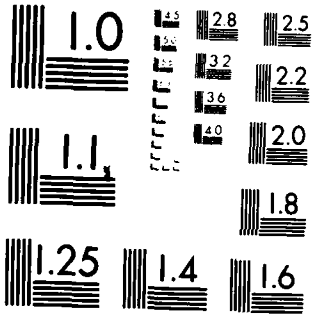

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MITIGATION OF ANGLE OF ARRIVAL JITTER EFFECTS FOR SITE DEFENSE RADAR OPERATION IN A NUCLEAR DUST CLOUD PEDESTAL

Carl J. Lauer
Mission Research Corporation
P.O. Drawer 719
Santa Barbara, California 93102

1 February 1982

Technical Report

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Angle of arrival fluctuations on radar signals can cause inaccuracies in target location. This report examines pulse integration, frequency agility, antenna size, command guidance, and triangulation as mitigants to angle-of-arrival error.

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SECTION 1

INTRODUCTION

Angle-of-arrival (AOA) fluctuations from propagation through a nuclear dust cloud pedestal can potentially degrade the tracking precision of a sight defense radar (SDR). This note discusses the applicability of various techniques for mitigating this effect. The emphasis taken here is to estimate their theoretical effectiveness, although comments regarding feasibility are also made.

SECTION 2
BACKGROUND

AOA jitter is caused by turbulence-induced index of refraction fluctuations along the dust cloud propagation path. The magnitude of the jitter may be specified by the standard deviation (σ_α) of its amplitude distribution. For our purposes σ_α does not represent the AOA fluctuations on the received wavefront directly, but instead refers to the AOA jitter measured by an antenna which intercepts some portion of the fluctuating wavefront. As a result, the effects of a finite antenna aperture size are always included when referring to σ_α. The nominal antenna diameter assumed is 2 meters.

Predictions for σ_α have been made by this author (Reference 1) and others. σ_α has been found to be directly proportional to the integrated mass of dust along the radar sight path and this quantity is largely unknown. Uncertainty in our knowledge of the dust turbulence structure and its material properties have led to additional but smaller variations in the predictions. Unfortunately, there is insufficient experimental data to allow accurate forecasts of the nuclear dust cloud pedestal environment. Since the radar propagation effects depend entirely on the dust cloud environment, inaccuracies result in predicting the propagation effects. However, for many situations, using nominal values for the amount of material lofted, σ_α has been found to be large enough to potentially degrade radar performance.

There are various means by which the loss in tracking precision caused by nuclear pedestal cloud AOA jitter may be at least partially mitigated. The techniques we will consider are listed below.

- Pulse integration
- Frequency agility
- Antenna size increases
- Command guidance
- Range triangulation

While the above list is incomplete, it is thought to include those techniques with the most practical importance.

SECTION 3
DISCUSSION OF MITIGATION TECHNIQUES

PULSE INTEGRATION

Integrating or averaging the recorded AOA samples over time is a conventional method to reduce the effect of jitter on an estimation of the mean AOA. For N independent samples, the standard deviation in estimating the mean AOA ($\sigma_{\bar{\alpha}}$) is related to the standard deviation in the raw AOA (σ_{α}) by

$$\sigma_{\bar{\alpha}} \approx \sigma_{\alpha}/\sqrt{N} \qquad (1)$$

With N made sufficiently large, $\sigma_{\bar{\alpha}}$ may be made as small as desired. Of course, in any real system the samples would undergo some form of low pass filtering, but for our analysis this is equivalent to averaging a finite number of samples.

Several factors are seen to limit the increased tracking precision attainable for SDR applications through this technique. The radar system must be capable of recording and processing sufficient samples in the available tracking time. Since present radar concepts allow for the ability to meet such a requirement, this is not seen to seriously impact the feasibility unless the necessary decrease in the raw jitter becomes excessive.

A second consideration is that of sampling independence. The reduction in $\sigma_{\overline{\alpha}}$ predicted by Equation 1 is valid only when the N samples are uncorrelated. As a means of addressing this subject, calculations were made to predict the temporal response of the AOA jitter. Following Reference 2, the normalized frequency spectrum of the AOA fluctuations is given by

$$W_\alpha(f) = C \cdot \frac{\sin^2(\pi Df/V)}{f^{8/3}\left[1+\left(\frac{1.07\ V}{2\pi fL_o}\right)^2\right]^{4/3}} \qquad (2)$$

where

D = antenna diameter
f = frequency
L_o = outer scale of turbulence
V = mean flow velocity of dust perpendicular to the radar's line of sight
and C = a normalization constant chosen such that

$$\int_0^\infty W_\alpha(f)\ df = 1 \quad . \qquad (3)$$

Here it was assumed that to first order the time behavior could be obtained by Taylor's frozen flow hypothesis. In this approximation, the main contribution to the change in the radar propagation path with time is due to the mean dust flow velocity perpendicular to the radar sight path. The additional assumptions were made of plane wave propagation through a homogeneous layer of turbulence having a Kolmogorov distribution.

Figure 1 shows the frequency spectrum predicted by Equation 2 where the values of V chosen reflect those thought to be reasonable limits for proposed radar operation in a nuclear dust cloud. V=300 meters/second roughly corresponds to the peak particle velocity generated for a shock wave peak overpressure of about 30 psi. V=30 meters/second would be representative of velocities expected after passage of the blast wave overpressure positive phase.

The time autocorrelation of the AOA fluctuations is obtained by taking the Fourier transform of their frequency spectrum. Figure 2 shows the autocorrelation of the AOA fluctuations predicted by transforming the frequency spectra of Figure 2. It is seen that they are approximately gaussian in shape, with standard deviations $\sigma_\tau \approx .04, .004$ seconds for V=30 and 300 meters/second, respectively.

Using these decorrelation times we may comment on the radar sampling rates allowable that would guarantee sampling independence. For a gaussian autocorrelation with standard deviation σ_τ, the necessary time interval for sampling independence (T_I) is given by

$$T_I \approx \sqrt{2\pi}\ \sigma_\tau \tag{4}$$

Sampling at a more rapid rate gives practically no new information and no improvement on a true estimate of the mean (see Reference 3). From Equation 4 $T_I \approx .1, .01$ seconds for the cases V=30, 300 meters/second respectively. These sampling intervals fall within the interesting range of sampling times under consideration for propcsed SDR operation.

We conclude that the subject of sampling independence should be carefully considered when assessing the reduction in angle errors achievable through the use of pulse integration.

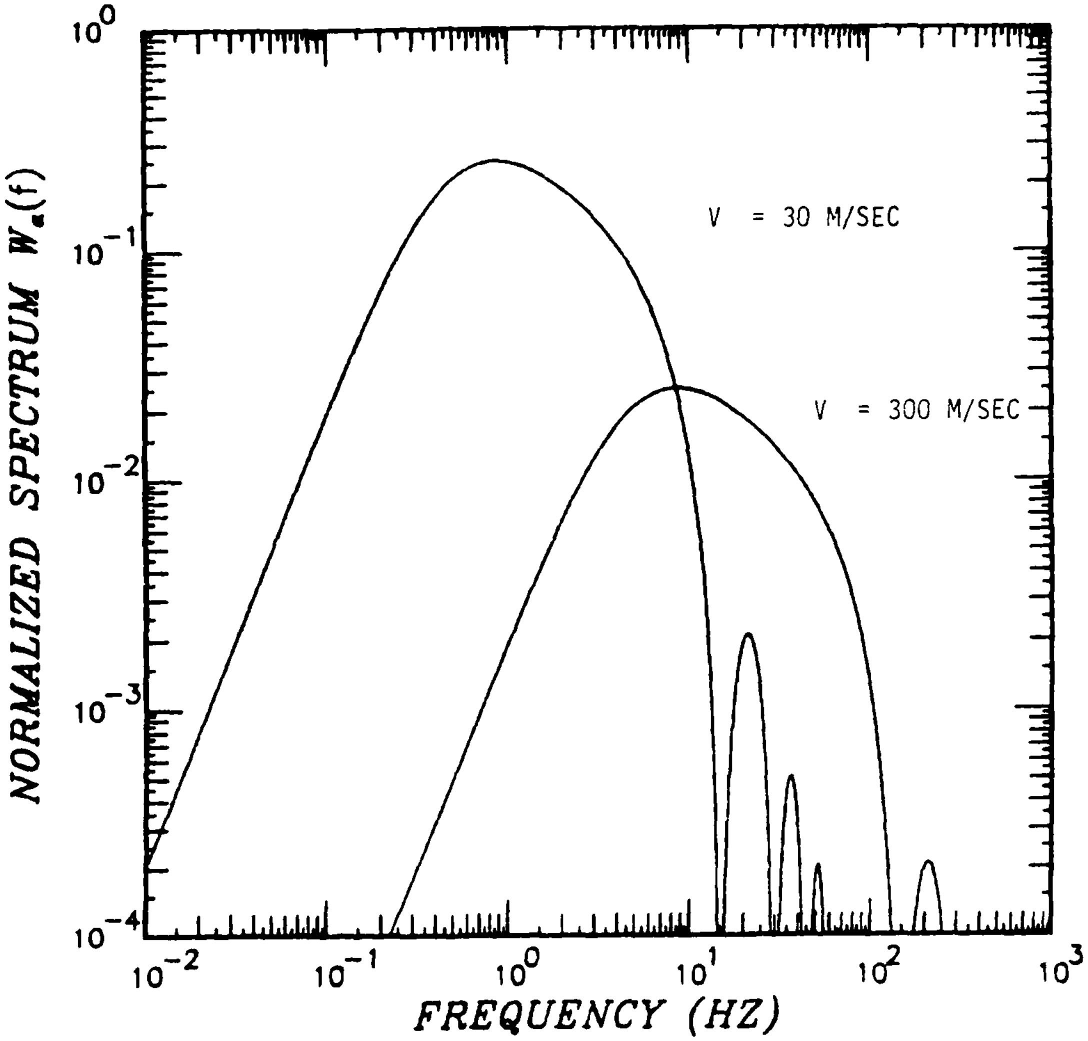


Figure 1. Normalized spectrum of angle-of-arrival fluctuations for a 2 meter diameter antenna. (Assumes Kolmogorov turbulence with an outer scale of 10 meters.)

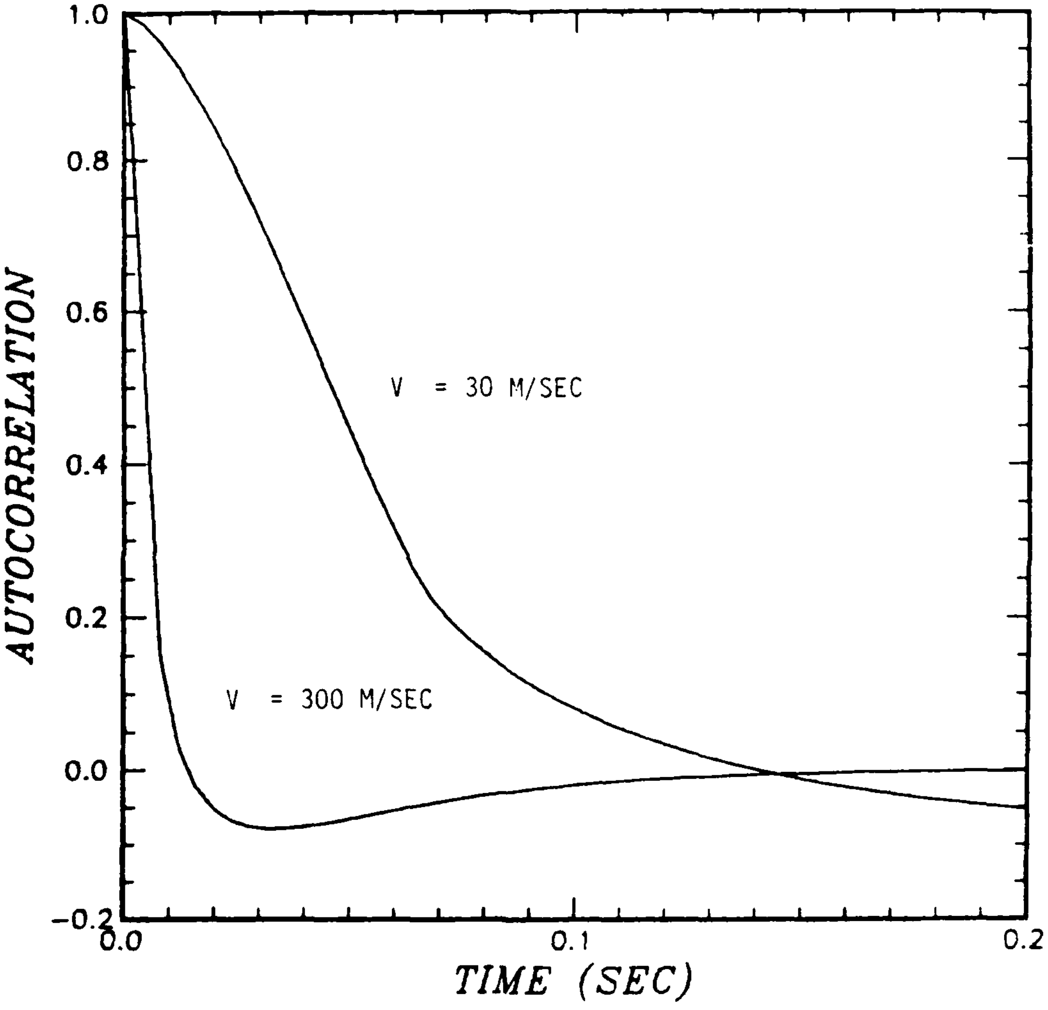


Figure 2. Autocorrelation of angle-of-arrival fluctuations for a 2 meter diameter antenna. (Assumes Kolmogorov turbulence with an outer scale of 10 meters.)

FREQUENCY AGILITY

A frequency agile radar performs multiple frequency RF transmissions during a single look at a target. When the frequency steps result in AOA returns which are uncorrelated, averaging them will allow the equivalent reduction in jitter as is achievable through pulse integration of this number of independent samples recorded over time. The merits of frquency diversity may be evaluated by estimating the correlation between the AOA of two wavefronts received simultaneously after propagating along the same sight path at different RF frequencies.

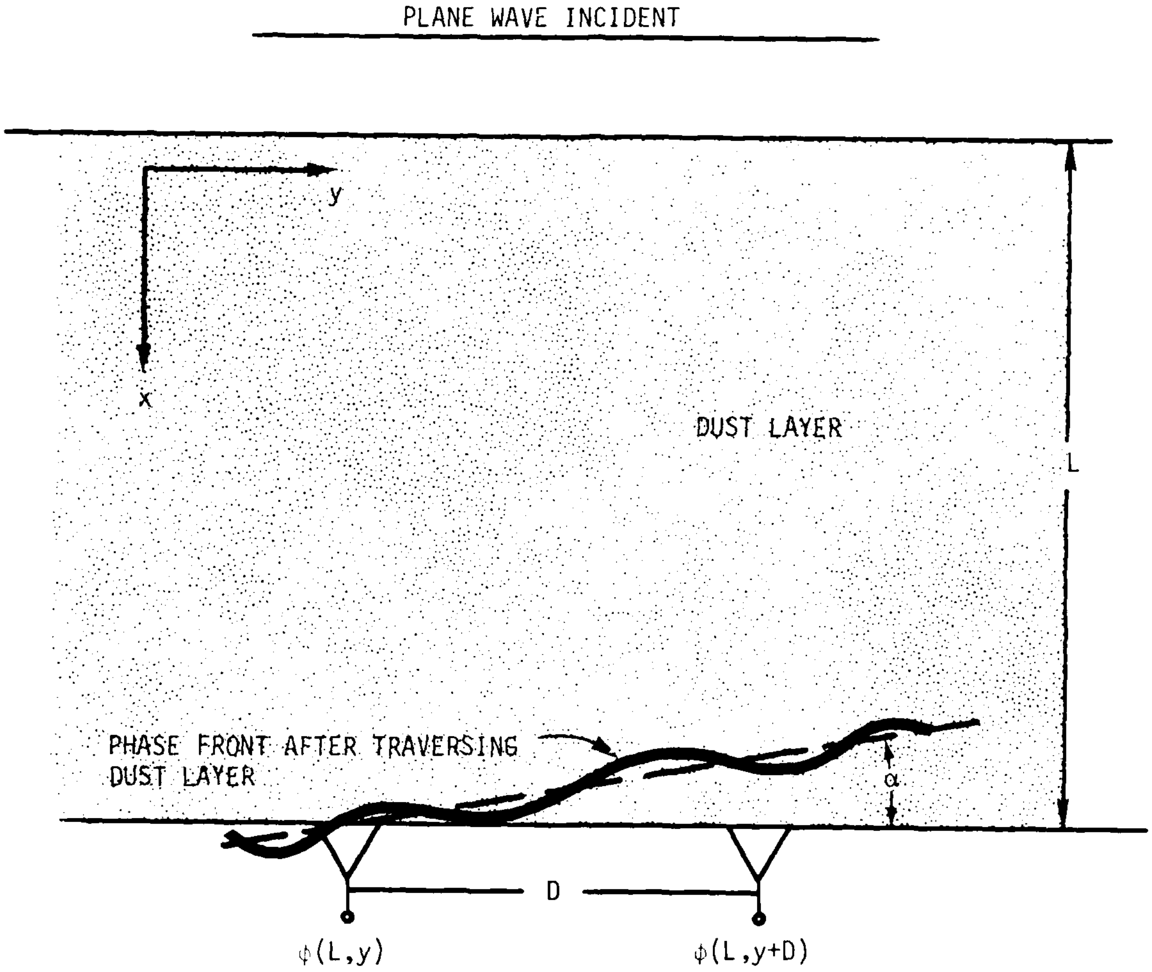
Figure 3 shows the perturbation in the arrival angle of a received wavefront after propagating a distance L through a dust layer. Using the simple phase interferometer shown to model the antenna angle estimator, the AOA is given in the small angle approximation to be

$$\alpha \approx \frac{\lambda}{2\pi D} \cdot \{\phi(L,y) - \phi(L,y+D)\} \tag{5}$$

where y is the coordinate transverse to the propagation direction and $\{\phi(L,y)-\phi(L,y+D)\}$ is the difference in phase measured by the interferometer of size D.

A useful simplification for calculating the phase difference is to apply geometrical optics methods. This may be justified by noting that diffraction effects have been found to have very little impact on predictions for phase front perturbations when the propagation path length L is such that (see Reference 4)

$$L \leq \Lambda y^2/\lambda \tag{6}$$



$$\alpha \approx \frac{\lambda}{2\pi D}\left(\phi(L,y) - \phi(L,y+D)\right)$$

Figure 3. Estimation of the angle-of-arrival by a phase interferometer.

where λ is the RF wavelength, and Δy is the distance perpendicular to the mean phase front over which phase differences are measured. For an AOA measurement, Δy becomes the antenna diameter D. Using the nominal antenna diameter of 2 meters and an RF wavelength of 3 cm, we see that geometrical optics techniques are applicable for path lengths of about 130 meters or less, and this distance is comparable to the longest path lengths of interest.

In the geometrical optics approximation and for plane wave propagation in the x direction, the phase difference is given by

$$\phi(L,y) - \phi(L,y+D) = \frac{2\pi}{\lambda} \int_0^L (n_m(x,y) - n_m(x,y+D))dx \qquad (7)$$

where the integration traverses the pedestal cloud along parallel rays spaced a distance D apart. $n_m(x,y)$ and $n_m(x,y+D)$ are the indices of refraction of the pedestal cloud medium at positions along the parallel rays.

On substitution of Equation 7 into Equation 5 we obtain

$$\alpha = \frac{1}{D} \int_0^L (n_m(x,y) - n_m(x,y+D))dx \qquad (8)$$

and the AOA is seen to not depend on RF frequency except through possible frequency dispersion of the medium.

The frequency dispersion of the medium may be obtained as a function of the properties of the bulk material lofted into the pedestal cloud through the Clausius-Mossotti formula (see Reference 5)

$$n_m = 1 + \frac{3}{2}\frac{\rho_m}{\rho_b} \mathrm{Re}\left[\frac{n_b(F)^2-1}{n_b(F)^2+2}\right] \tag{9}$$

where

ρ_m = mass density of the pedestal cloud medium
ρ_b = mass density of the bulk material
$n_b(F)$ = complex index of refraction of the bulk material as a function of RF frequency.

Using Equation 9 to substitute for $\left(n_m(x,y) - n_m(x,y+D)\right)$ in Equation 8 we obtain

$$\alpha = \frac{3}{2\rho_b D} \mathrm{Re}\left[\frac{n_b(F)^2-1}{n_b(F)^2+2}\right] \int_0^L \left[\rho_m(x,y) - \rho_m(x,y+D)\right]dx \tag{10}$$

and the effect of RF frequency variation may be expressed simply as

$$\alpha \approx \mathrm{Re}\left[\frac{n_b(F)^2-1}{n_b(F)^2+2}\right] \quad . \tag{11}$$

In Table 1 we list the bulk indices of refraction for representative materials of interest at UHF and X-band and the resultant variation in AOA predicted by Equation 11. It is observed in Table 1 that the variation in AOA with frequency is small for each of the materials considered. For the approximate decade frequency change from UHF to X-band there is a maximum variation of about 15% in the AOA. Therefore we expect that the frequency dependence of the AOA for a dust cloud consisting of a mixture of these materials would be small also.

Table 1. Variation in AOA predicted by Equation 11.

Material	$n_b(F)$	$\alpha \approx \mathrm{Re}\left[\frac{n_b(F)^2-1}{n_b(F)^2+2}\right]$	Reference
Sand (UHF)	2.2 - .090j	.56	6
Sand (X-band)	2.0 - .035j	.49	6
Caliche (UFH)	2.5 - .133j	.64	6
Caliche (X-band)	2.2 - .043j	.56	6
Water (UHF)	8.8 - .120j	.96	7
Water (X-band)	7.5 - 2.300j	.96	7

The results of this section may be summarized as follows: In considering the effects of RF frequency variations, we first observe that for the propagation path lengths and antenna size of interest, diffraction effects can be neglected. Then, using geometrical optics theory we show that the remaining RF frequency varation is due to the frequency dispersion properties of the medium, and this effect is also found to be very small. As a result, we predict very little decorrelation in the AOA within the RF frequency ranges of interest. Thus, we do not expect that frequency agility will be an effective mitigation technique.

ANTENNA SIZE

Increasing the size of an antenna has been shown to reduce the level of jitter on the antenna's AOA estimate (Reference 8). The mechanism responsible for this reduction is the antenna aperture averaging of the received phase front.

Calculations were performed to evaluate the dependence of σ_α on antenna size. The results are shown in Figure 4. The formulation described in Reference 1 was utilized to make these calculations. The

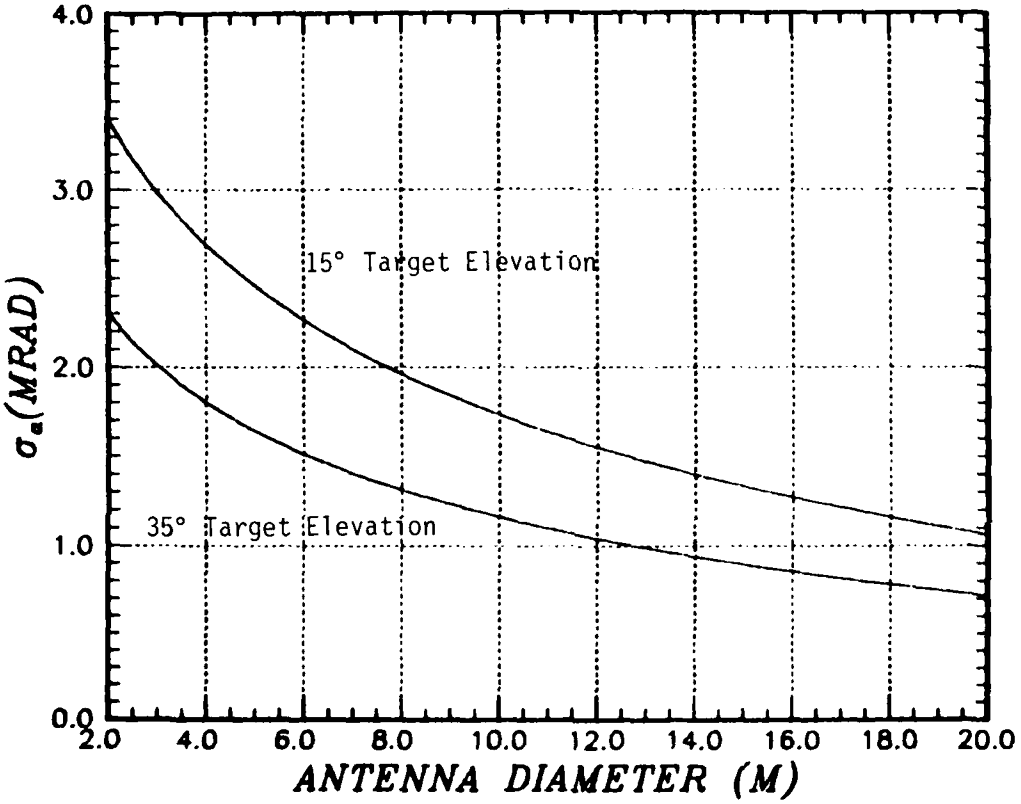


Figure 4. RMS angle-of-arrival fluctuations vs antenna diameter. (Assumes Kolmogorov spectrum with an outer scale of 10 meters.)

pedestal cloud dust density assumed here represents an environment where 2 centimeters of scoured caliche have been distributed vertically with an exponential scale height of 6 meters. A Kolmogorov turbulence spectrum with an outer scale of 10 meters has also been assumed. Antenna diameter variations of from 2 to 20 meters for target elevations of 15 and 35 degrees are considered. The important trend borne out is that AOA jitter decreases very slowly with increasing antenna size. It is seen that doubling the antenna diameter from the nominal 2 meters to 4 meters achieves less than a 15 percent reduction in σ_α, such a small reduction being insignificant compared to uncertainties in knowing the dust environment. Portability, survivability, and cost put obvious constraints on the maximum allowable antenna size whereas it is suggested by Figure 4 that it would take a very large antenna to achieve substantial reductions in σ_α.

We conclude here that mitigation of AOA effects by merely increasing antenna size is not feasible.

COMMAND GUIDANCE

The location of the SDR and interceptor launch point relative to a "keep-out" zone which they are to defend may impact the effect of AOA errors on miss distance when command guidance is used. Referring to Figure 5, locating the SDR and interceptor launch point in the vicinity of their defended "keep-out" zone results in trajectories where the angular deviation between target and interceptor tends to be small during a significant fraction of the interceptor's flight. For this part of the flight, the AOA jitter on the target echoes will be correlated with the AOA jitter associated with tracking of the interceptor, since the returned signals from each will traverse nearly identical paths through the pedestal cloud. Then, if the guidance commands to the interceptor are proportional to the angular separation between the target and interceptor, the AOA jitter on the two angle estimates would be removed through subtraction

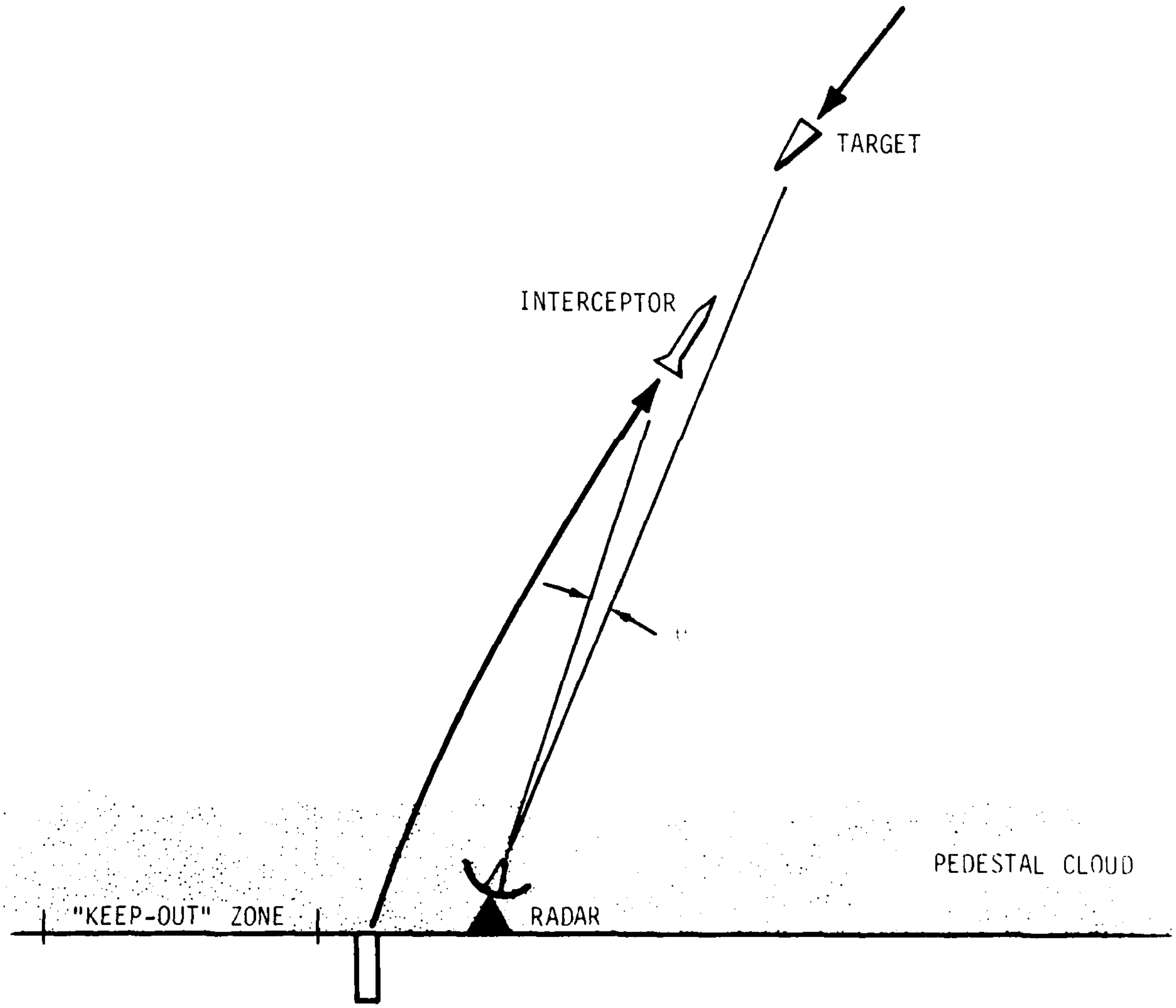


Figure 5. Command guidance.

when constructing the guidance signals. This implies that there is a possible advantage in choice of siting for the SDR and interceptor that would encourage a line of sight type interception geometry.

It is desirable to estimate the angular alignment necessary for this effect to be significant. This may be indicated by calculating the correlation between the fluctuating part of the AOA for the returned signals from two targets as a function of their angular separation. As a simplification we once again apply results from geometrical optics theory which we have previously shown to be applicable.

From Reference 2, the correlation of the AOA jitter for the component of the jitter in the direction of the targets' angular separation may be expressed as

$$R(\theta) = \frac{3}{16} \frac{(1+x)^{8/3} - (1-x)^{8/3} - 2x^{8/3}}{x} \quad ; x \leq 1 \qquad (12)$$

$$R(\theta) = \frac{3}{16} \frac{(1+x)^{8/3} + (x-1)^{8/3} - 2x^{8/3}}{x} \quad ; x > 1 \qquad (13)$$

where

$$x = \frac{2L}{D} \tan(\theta/2) \qquad (14)$$

L = dust cloud propagation path length

D = antenna diameter

θ = angular separation of the targets.

The additional assumption of a Kolmogorov dust cloud turbulence spectrum has been made. The correlation has been normalized to be unity for zero angular separation.

Figure 6 shows the correlation predicted by Equations 12 and 13 as a function of θ for several propagation path lengths and an antenna diameter of 2 meters. It is seen that there is still a high (≈85%) correlation in the AOA jitter for an angular separation of 10 degrees for the 10 meter path, and a moderate (≈40%) correlation at 10 degrees for the 100 meter path. This implies that significant reductions in the AOA jitter-caused guidance errors could be made for target and interceptor line of sight separations under 10 degrees. It is also seen that the predicted correlation increases quickly with decreasing θ so that even larger reductions in AOA jitter-caused guidance errors would be possible if the angular separations were expected to be much smaller than 10 degrees.

The rather high correlations result from the fact that the pedestal dust cloud is by nature of low height leading to short propagation paths. Accounting for the uncertainty in current knowledge of the dust density scale heights of a nuclear dust cloud pedestal, scale heights under 10 meters are possible. If a scale height under 10 meters is applicable this would also lead to higher predicted correlations. Correspondingly, path lengths longer than 100 meters would decorrelate faster with increasing target separation.

A further remark concerning these predictions is that they apply for comparison of simultaneous returns from the two separated targets. The time delay in sampling which can be safely allowed before there would be a reduction in the predicted correlation can be estimated by referring back to Figure 2.

The practicality of this geometry-sensitive technique depends on many factors. One consideration is how closely the interceptor's trajectory would actually follow the radar's line of sight to the target for this type of engagement. Assuming close alignment during say the last half of the interceptor's flight, then the effect of giving correct guidance over this time only must be assessed as to its impact on miss distance.

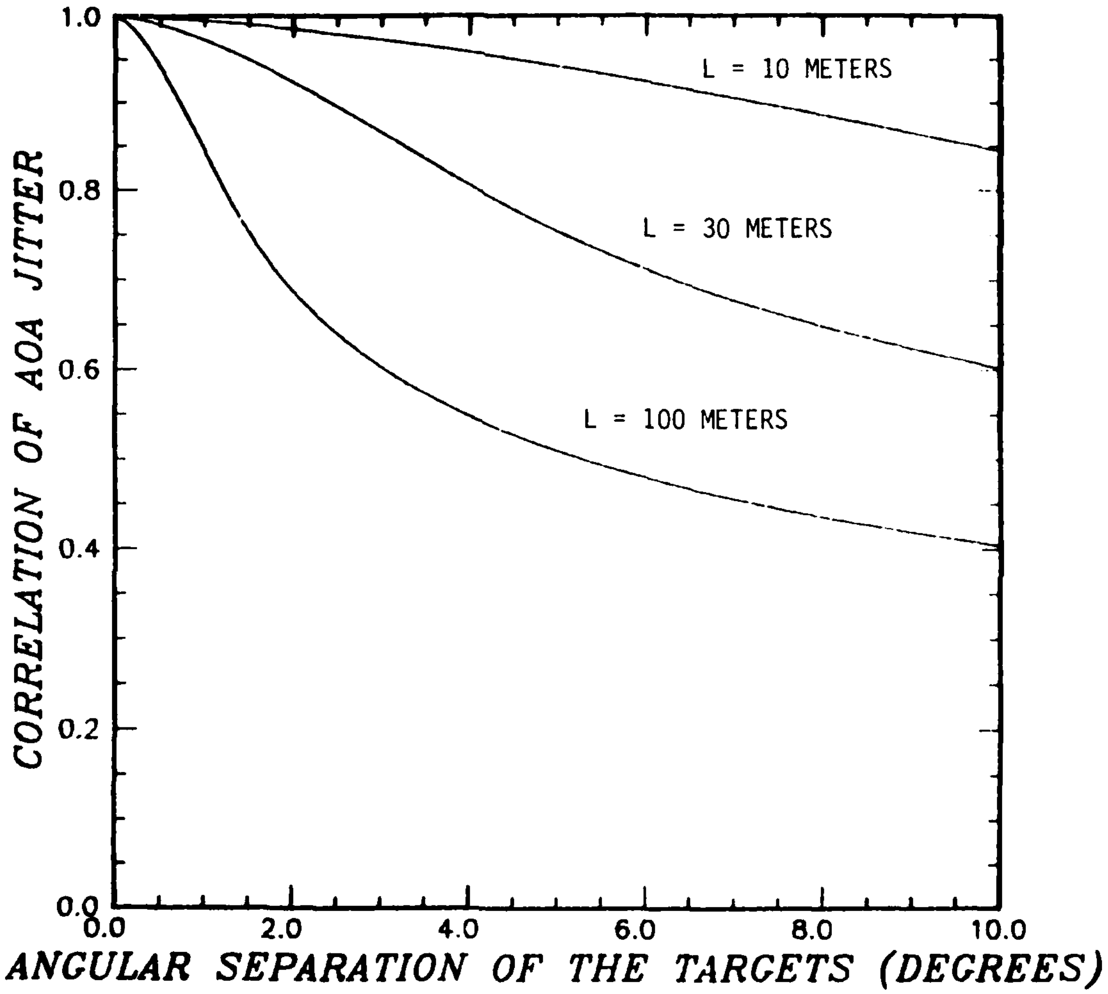


Figure 6. Correlation between AOA jitter for two separate targets as a function of their angular separation for propagation path lengths of 10, 30 and 100 meters.

There is also a possible degradation in the operating environment for the SDR when located close to the zone it is to defend. We will not pursue these questions here.

RANGE TRIANGULATION

The use of netted monostatic radars to determine target direction using range-only data has been suggested (Reference 9) as a possible alternative to conventional methods utilizing a single radar to sample the phase of the returned wave front. The advantage of this technique is that range measurement inaccuracies from propagation through a pedestal dust cloud can be shown to be completely negligible. This implies that the angle errors from dust cloud propagation effects would be small compared to the nominal angle resolution of a range triangulation system.

The design requirements for such a system to perform precision angle tracking must be evaluated in order to assess its feasibility. Target location in 3 dimensions requires a minimum of 3 range measurements, commonly referred to as trilateration. A treatment of the location accuracy for this general case is given by Skolnik in Reference 10.

As a simplification, we assess the angle sensing resolution afforded by a single pair of radars. Referring to Figure 7, the radar ground spacing is X_G and the range estimates R_1 and R_2 are compared to find the target elevation angle (β) which is measured relative to the baseline connecting the radars. Then for a range measurement error ΔR, the error in estimating β is approximately equal to

$$\Delta\beta \approx \frac{\Delta R}{X_G \sin\beta} \qquad (15)$$

when the target range is much larger than X_G.

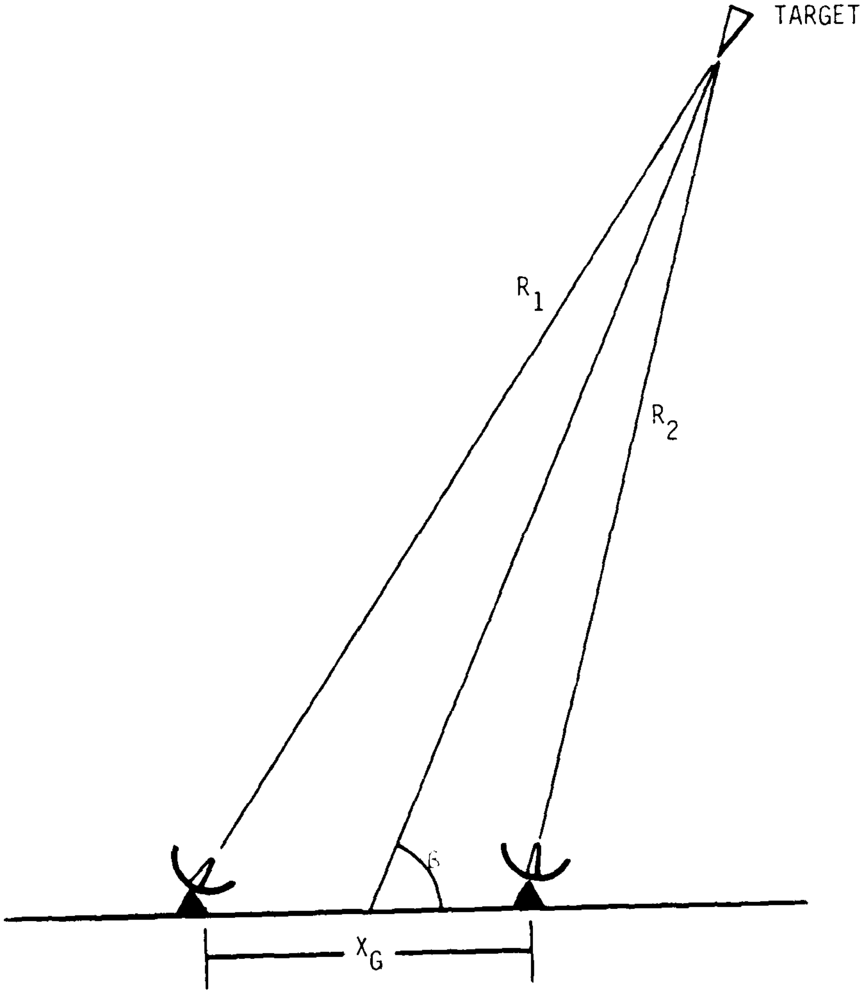


Figure 7. Range triangulation.

Assuming the nominal range error is 5 meters, then for a target elevation of 90°, Equation 15 predicts a required ground spacing of 5 kilometers to achieve milliradian angle accuracy. For milliradian angle accuracy at 15° target elevation the required spacing increases to about 20 kilometers. These examples show that quite large spacings are required to attain milliradian angle accuracy for 5 meters of range error. If greater range accuracy is attainable, the necessary spacing will scale down accordingly.

The main drawback to the feasibility of such a system is the necessity to maintain data communication links between the various radars and a data processing center. These communications links are a source of increased system complexity, cost, and vulnerability not present in the single monostatic case.

SECTION 4

CONCLUSIONS

AOA jitter from radar propagation through a nuclear dust cloud pedestal has previously been identified to be a potential source of degradation for operation of a SDR. A limited list of mitigation techniques has been evaluated. Key results from this analysis may be summarized as follows:

- Predictions for reducing jitter through pulse integration should take account of the time correlation of the fluctuating AOA samples. Maximum sampling rates which would provide independence are estimated to be in the 10 to 100 Hz range.
- Frequency agility has been found to be quite ineffective as a means to generate independent AOA estimates.
- Increasing the antenna size is an ineffective means of reducing jitter.
- A method for reducing the impact of AOA jitter on miss distance has been identified for command guidance applications. The effectiveness is dependent on interception geometries that maintain a small angular separation between target and interceptor. Judicious siting of the SDR and interceptor launch points could encourage favorable interception geometries.
- Using several radars to perform direction finding through range measurements alone would entirely remove the effects of pedestal cloud AOA jitter. However, very large distances (≈ 10 km) between the radars would be required to attain reasonable angle tracking precision. The necessity to maintain data communication links over these distances would increase the vulnerability of the system to a stress environment.

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Strategic Systems Proj Ofc
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